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SDIO/IST ULTRASHORT WAVELENGTH

By

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Final Report
For the period ended April 30, 1994

Prepared for
Naval Research Laboratory
4555 Overlook Ave., S.W.
Washington, D.C. 20375-5000

Under
Research Contract N00014-90-K-2003
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Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508-0369

June 1994

SDIO/IST ULTRASHORT WAVELENGTH LASER
FINAL REPORT

"Mössbauer and Gamma-Ray Studies for Grasers"
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I. GENERAL REMARKS

I a. Technical Overview

Ideas of making gamma-ray lasers and focussing gamma rays have fascinated scientists for many years. Over the past 30 years a number of important scientific and technological advances have been made which motivated me to propose the research whose results are presented here. Such developments included; the discovery of the Mössbauer Effect, the ability to fabricate perfect single crystals, the ability to structure materials on an atomic scale, the development of synchrotron radiation facilities, and the experimental realization of the consequences of the so-called "dynamical" theory of x-ray diffraction. Although the consequences of the dynamical theory using x radiation have been thoroughly explored, relatively little research had been done using gamma radiation. The dynamical theory predicts that radiation can pass through perfect single crystals that are 100 times thicker than one would normally expect. A specific goal of the proposed research was to search for this "anomalous transmission" effect using gamma radiation. This was to be accomplished by making measurements on radioactively doped single crystals. Furthermore, some of the samples were to contain sufficient resonant nuclei in the ground state so that transmission should not be possible due to nuclear resonant absorption. In such a case, anomalous transmission of resonant radiation would imply an enhancement of the radiative channel: an " anomalous temporal decay" effect.

An observation of any such "speed-up" in the nuclear-decay rate would be quite significant. It would imply that a collective-coherent nuclear radiating state can be produced in a radioactive sample. Our results, presented below, suggest that both the "anomalous transmission" effect, and the " anomalous temporal decay" effect do occur.

My general goal in proposing this research was to begin to provide a foundation of experimental evidence in this new field of gamma-ray optics which may lead to technical advances that parallel those in atomic, optical, and solid state physics, e.g., focusing, lasers, enhanced or inhibited spontaneous emission, coupled atom-cavity modes, and superradiance.

I b. Student Support

During the course of this contract two students, Walter C. McDermott III, and David E. Johnson have started doing research for their Ph.D. dissertations. Because of the funds provided by this contract, they have been able to make substantial progress. They should finish their research in about one more year.

II. TECHNICAL BACKGROUND

The recoil-free emission and/or absorption of gamma radiation, i.e., the Mössbauer Effect[1] (ME), that can occur when certain nuclei are imbedded in solids, plays a central role in our research. In the first place, the energy spectral distribution in such processes has a purity that approaches the theoretical limit governed by the Heisenberg uncertainty principle. In addition, energetic coherence is preserved in these recoil-free processes. Furthermore, the photons involved in such processes tend to have coherence lengths on the order of meters: quite long compared to sample thicknesses. This may allow nuclei, which are separated far from each other in a sample, to interact collectively.

Since high energy x rays and low energy gamma rays only differ by virtue of their sources, the well-established field of x-ray diffraction in crystals[2] is also a subject of considerable relevance for our research. One generally thinks of gamma radiation as having a shorter wavelength than x radiation, but this distinction is clearly far from exact. Consider, for example, the lowest nuclear energy transition in ^{57}Fe. It has an energy of 14.4 keV and a corresponding wavelength of 0.86Å.

The most important contributions to our research from the field of x-ray physics have their origin in the "dynamical" theory[3] of optics. The consequences of this dynamical theory of x-ray diffraction manifest themselves most prominently when using highly perfect single crystals. In the dynamical theory one assumes that, in addition to the usual single Bragg scattering events, there are multiple Bragg scattering processes occurring inside the crystal. Exploiting the periodicity of a perfect single crystal, the dynamical theory uses a self-consistent approach in which the multiple scattering inside the crystal is the dominant mechanism. Thus, eigenmodes of the radiation field are established inside the crystal by superimposing all possible multiply scattered waves. This produces some very interesting results. In particular, it is possible for x radiation to pass through single crystals that are 100 times thicker than one would normally expect from the usual non-dynamical approach. This extraordinary "anomalous transmission" effect[4] has been observed using x rays, and is due to the fact that some modes of the radiation field inside the crystal have almost zero electric field at the atomic sites. Under these circumstances the mode only interacts weakly with the atomic electrons, leading to a suppressed photoelectric effect. These modes are often called "Borrmann modes."

From the gamma radiation point of view it is important to realize that, neglecting electronic effects, a single crystal containing resonant nuclei can also become non-absorbing[5,6] with respect to the resonant gamma radiation. The simplest way to view this, if one considers a nuclear transition of the M1 type, is to observe that the eigenmodes of the radiation field which have zero magnetic field at the nuclear sites do not experience nuclear resonant absorption, because in this case the electromagnetic wave is weakly coupled to the nuclei.

Now considering both electronic and nuclear resonant scattering and absorption, one is presented with situations rich with possibilities. If one considers a Borrmann mode the electric field at the lattice sites is close to zero, but the associated magnetic field and electric field gradient are relatively large, thus allowing such waves to interact strongly with nuclei at substitutional sites having M1 or E2 type transitions between the ground and low-lying excited states. From another point of view, if one has a nucleus, at a substitutional site in a crystal, in an excited state that decays by emitting M1 type radiation whose energy is such that the decay produces a Borrmann mode in the crystal, a similar nucleus located quite far away from the source nucleus can still interact with the emitted photon, if we exclude any intervening nuclear absorption. In this context one should recall that the correlation lengths for gamma-ray photons can be quite long. (The correlation length for the familiar 14.4-keV photon in the decay of ^{57}Fe is about 42 meters.)

In general, the theoretical research in gamma-ray optics has been far ahead of the experimental results. The main theoretical accomplishments are due to the efforts of Professors G.T. Trammell and J.D. Hannon in the USA, and Drs. Yu Kagan and A.M. Afanas'ev in Russia. Dr. G.V. Smirnov[7] and his collaborators have obtained significant experimental results over the past 25 years in Russia, and in more recent times Dr. U. van Bürck[7], in Germany, and collaborators have also made important progress. In addition, the availability of synchrotron radiation facilities has produced new possibilities for studying gamma-ray optics. The application of synchrotron radiation to nuclear-resonant processes has been spearheaded by Dr. E. Gerdau's[8] group in Germany. Important results have also come from work at Brookhaven[9] (NSLS), Stanford[10] (SLAC), Cornell[11] (CHESS), and most recently in Japan. There are several second and third generation synchrotron radiation facilities having higher photon energies and greater brightness in various stages of construction and design. Therefore, it appears that the future is bright for gamma-ray optics with respect to synchrotron radiation. However, there is an important point that needs to be made regarding the use of synchrotron radiation or radioactive sources in such experiments. As noted above, the correlation length for the 14.4-keV photon from the radioactive source ^{57}Co is about 42 m. On the other hand, the synchrotron radiation through a 50 meV band-width monochromator has a correlation length of only about 4 microns. Thus these two types of experimental approaches are complementary: in fact they do not give exactly the same information.

III. RESULTS

We report here our results in searching for the "anomalous transmission" and "anomalous temporal decay" of nuclear resonant radiation using internal sources located inside thick single crystals. Our samples are two iron single crystals of thicknesses 0.5 mm and 1.0 mm that have been doped on one side with ^{57}Co. From ordinary considerations, these samples are much too thick to allow any 14.4-keV radiation to pass through the crystal and out the other side. However, our results indicate that the 14.4-keV radiation is able to be transmitted through the crystals. Using coincidence techniques we have also examined the temporal decay of the

14.4-keV nuclear level under these circumstances.

As noted above, according to the dynamical theory of optics, it is possible for radiation to pass through crystals that are much thicker than one would normally expect. The Borrmann modes pass through the crystal with relatively little electronic absorption. On the other hand, a mode having a large electric field at the atomic sites will not be able to penetrate into the crystal. Therefore, from the optical reciprocity theorem, E1 multipole radiation coming from a nucleus located at a lattice site deep inside a thick crystal cannot radiate outside. Since the 14.4-keV nuclear level in ^{57}Fe is an M1 radiator, this radiation could conceivably propagate out of the crystal if one considers only electronic processes. However, in our case, we have used two iron single crystals of thicknesses 0.5 mm and 1.0 mm that have been doped on one side with ^{57}Co. Therefore, if the excited nuclei are at interstitial sites, the gamma radiation can not get out because of <u>electronic</u> absorption. (An anti-Borrmann mode is produced.) Furthermore, if the excited nuclei are located at substitutional sites, the 14.4-keV radiation in a Borrmann mode should still <u>not</u> be able to traverse the crystal because of <u>nuclear resonant</u> absorption. (There is a 2.2% abundance of ^{57}Fe in such unenriched crystals.) Therefore observation of the anomalous transmission effect in our case implies an enhancement of the radiative decay channel: a very important result if true.

The samples were prepared from selected iron single-crystal 3/8-inch disks of (100) orientation. After selection, ^{57}Co was evaporated onto each crystal in a 1/8-inch central spot and annealed at 850° C for 1/2 hour in an hydrogen atmosphere. Special care was taken to guard against any activity reaching the other side of the samples during these processes.

To search for the anomalous transmission effect[12] we took pulse-height spectra from both the doped and the undoped side of the two samples using a Ge solid-state detector. One set of results is shown in Fig. 1. The small 14.4-keV peak in the transmitted spectrum is labeled in the figure. As can be seen, this peak is in the same position as the more easily observed peak obtained in the pulse-height spectrum taken from the doped side. Calculating the transmitted intensity of the 14.4-keV radiation through these crystals using the normal mass absorption coefficients gives e^{-175} and e^{-350} for the two crystals, i.e., essentially no such radiation should be transmitted.

In an effort to observe the anomalous temporal decay[13,14,15] effect, we have done "time-filtering" measurements[16] using these ^{57}Co-doped iron single-crystal samples. (Perhaps it should be pointed out that the theoretical papers, references 13, 14, and 15, do not agree on the expected results.) Figure 2 shows a schematic diagram of the experimental arrangement. If the two detector positions, as shown in Fig. 2, are interchanged, the 14.4-keV radiation is not "filtered" since there is little iron to traverse; hence one expects to obtain the normal lifetime curve. Indeed, we obtained such a result as shown in Fig. 3. When the detectors were positioned as shown in Fig. 2 to measure the temporal characteristics of the transmitted, filtered radiation, we obtained a very different result. Initially, a very narrow "prompt" peak appeared rather quickly in the time spectrum. In fact, when we moved our energy selection "window" off the 14.4-keV peak, this prompt peak persisted. Such a result is shown in Fig. 4. This prompt curve is due to the geometrical experimental configuration in which the two detectors can "see" each other, and is the result of Compton scattering and escape events. By changing the orientation of the detectors, the prompt peak disappeared. Thus, this shape is not related to any anomalous temporal decay effect. However, if one does select the 14.4-keV peak and obtains sufficient statistics, the time spectrum shows a very interesting additional feature. This result is shown in Fig. 5. There is evidence of additional time structure not associated with the prompt peak. The dashed curve in Fig. 5 shows a simulated component that would correspond to the normal lifetime. In order to scale this component we set the value at 293 nsec to coincide with the experimental value. The shape of this feature of the experimental spectrum does not correspond to the normal lifetime. In our latest set of experiments we have eliminated the prompt peak by enclosing the sample in a recessed lead "washer." These results are shown in Fig. 6.

IV. CONCLUSIONS

These results suggest that both the anomalous transmission and anomalous temporal decay effects are occurring. In a very real sense these effects must be tied together as explained above. More research needs to be done to confirm such observations before any final conclusions can be drawn concerning these very important results. Gamma-ray lasers may, indeed, be possible.

V. REFERENCES

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VI. FIGURES

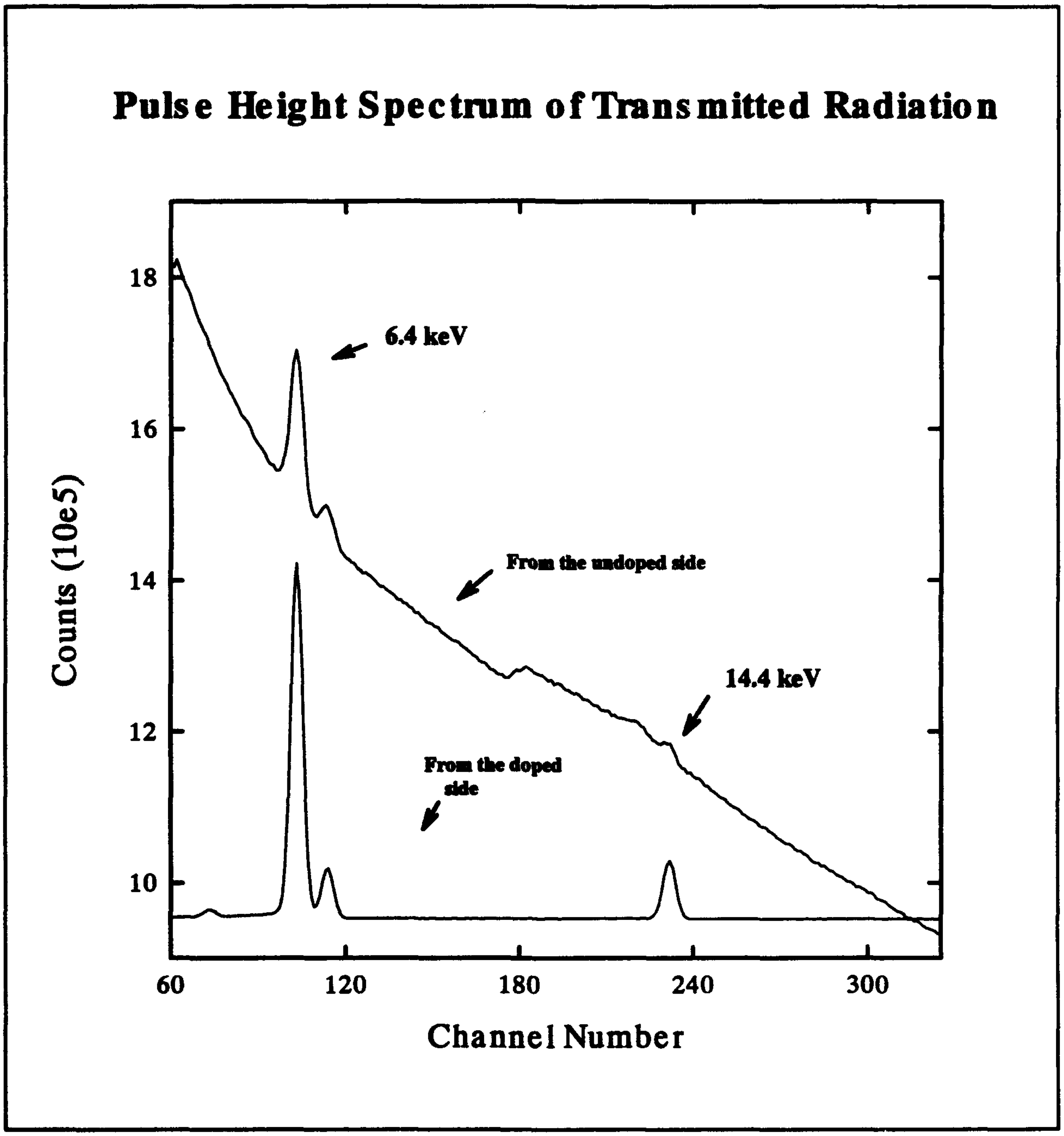

Figure 1. The pulse-height spectrum of the radiation transmitted through the 0.5-mm thick sample. Notice the small 14.4-keV peak. The lower curve is not to scale and is only shown for comparison purposes.

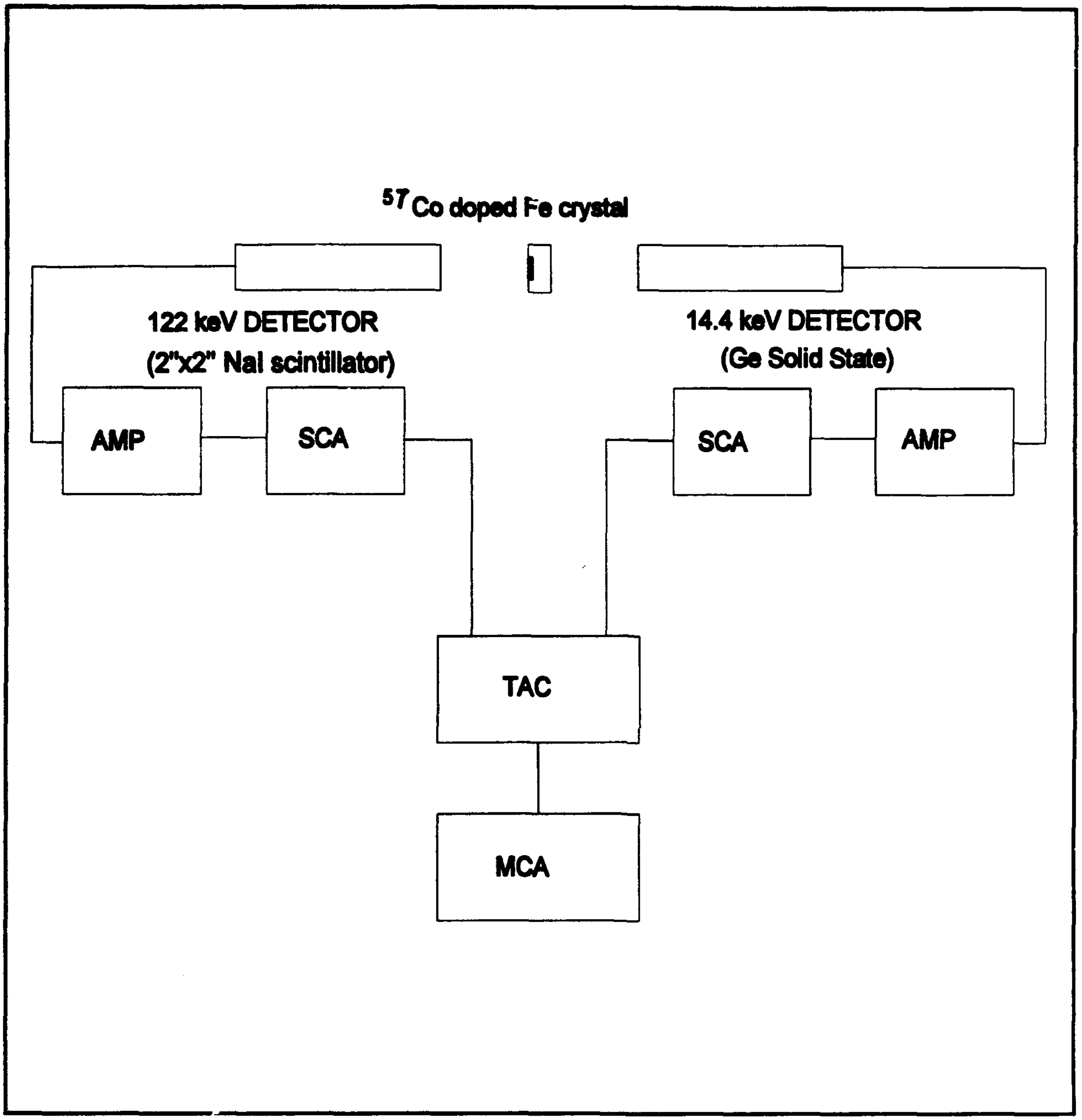

Figure 2. A schematic diagram of our apparatus to measure a nuclear lifetime curve. We use the the standard time-to-amplitude converter technique.

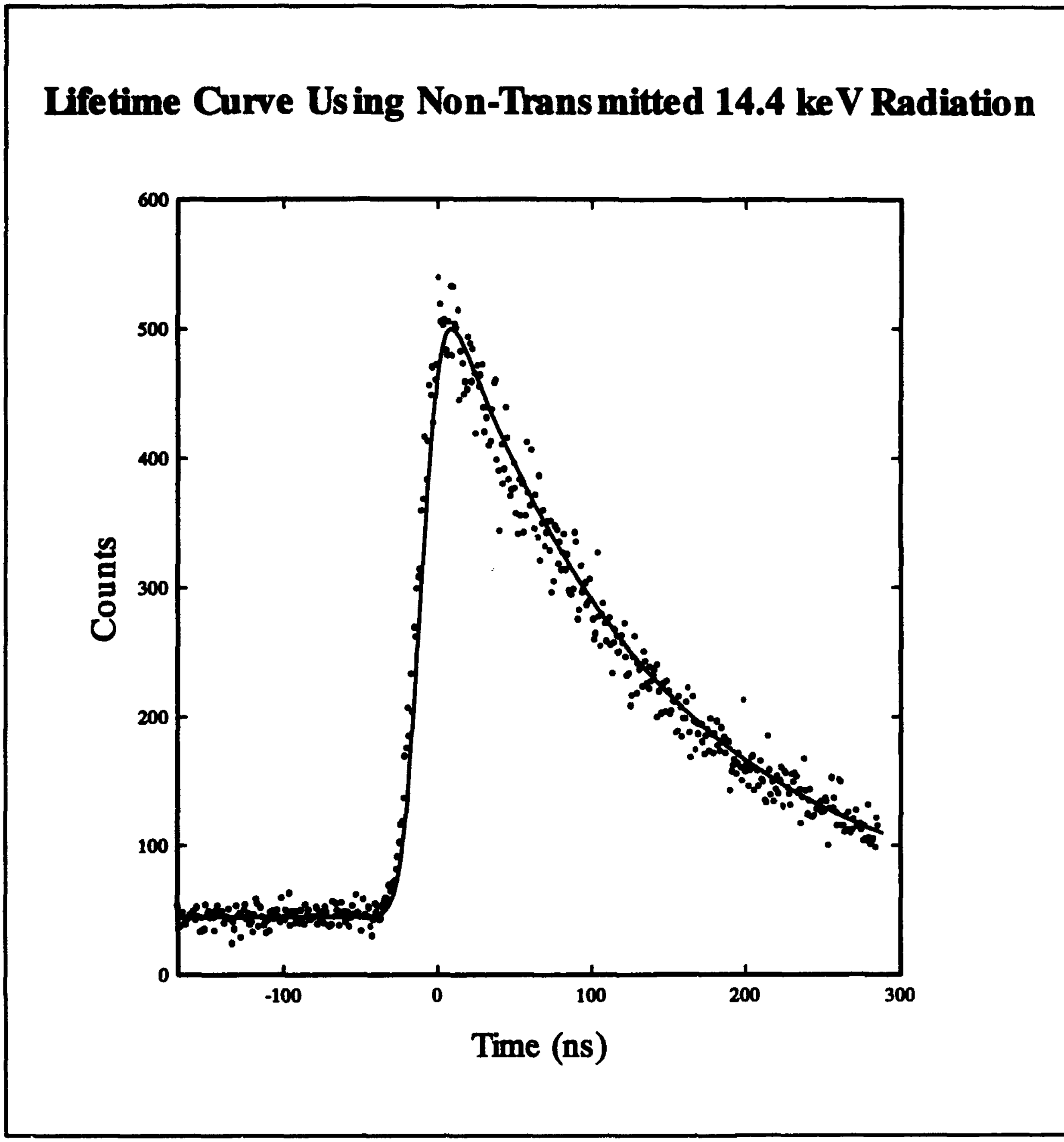

Figure 3. The normal lifetime curve obtained using the "unfiltered" 14.4-keV radiation. The solid curve is calculated using the normal 141-nanosecond lifetime.

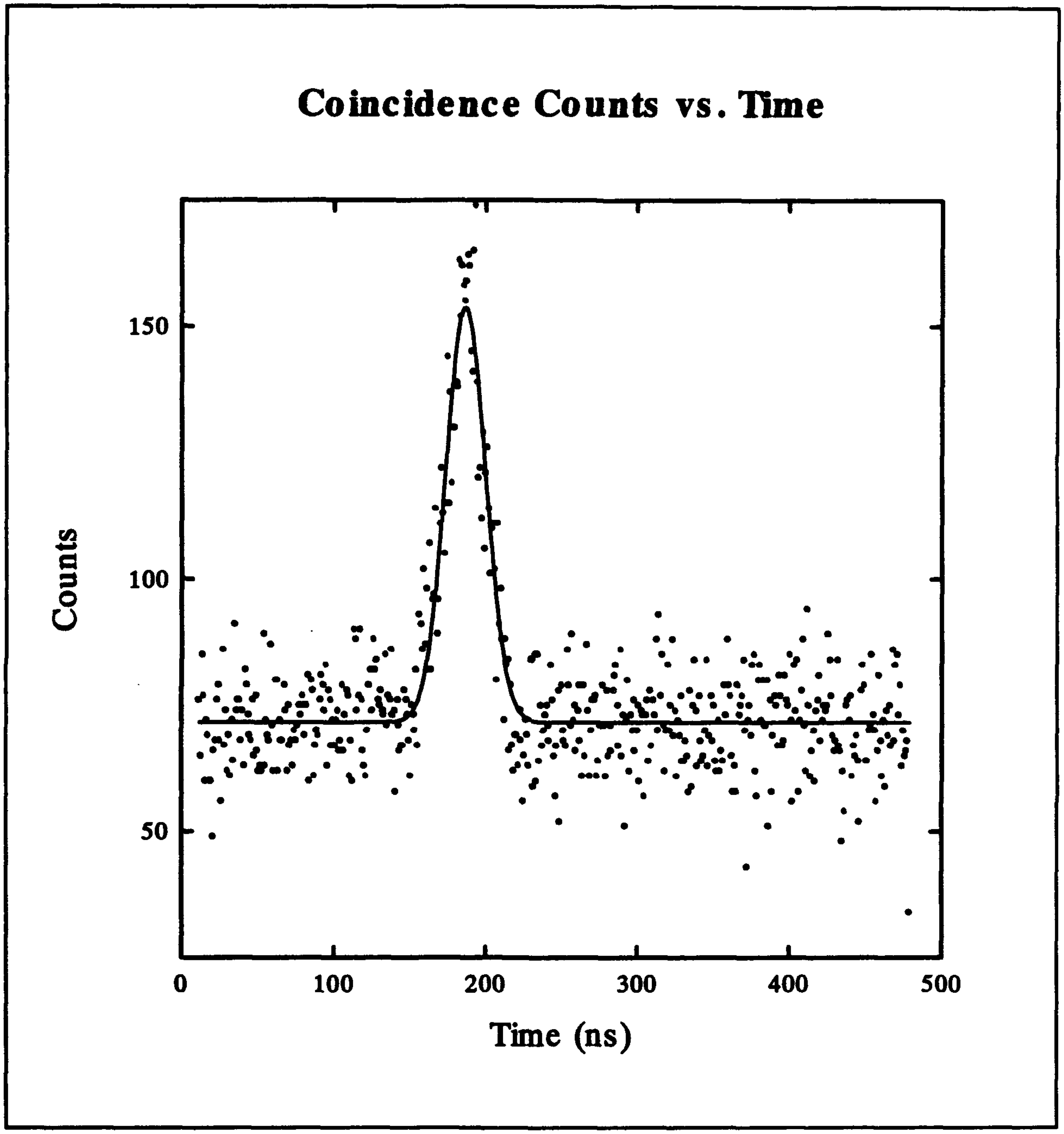

Figure 4. The "prompt", "lifetime" curve obtained when setting the 14.4 keV window <u>off</u> the 14.4 keV peak.

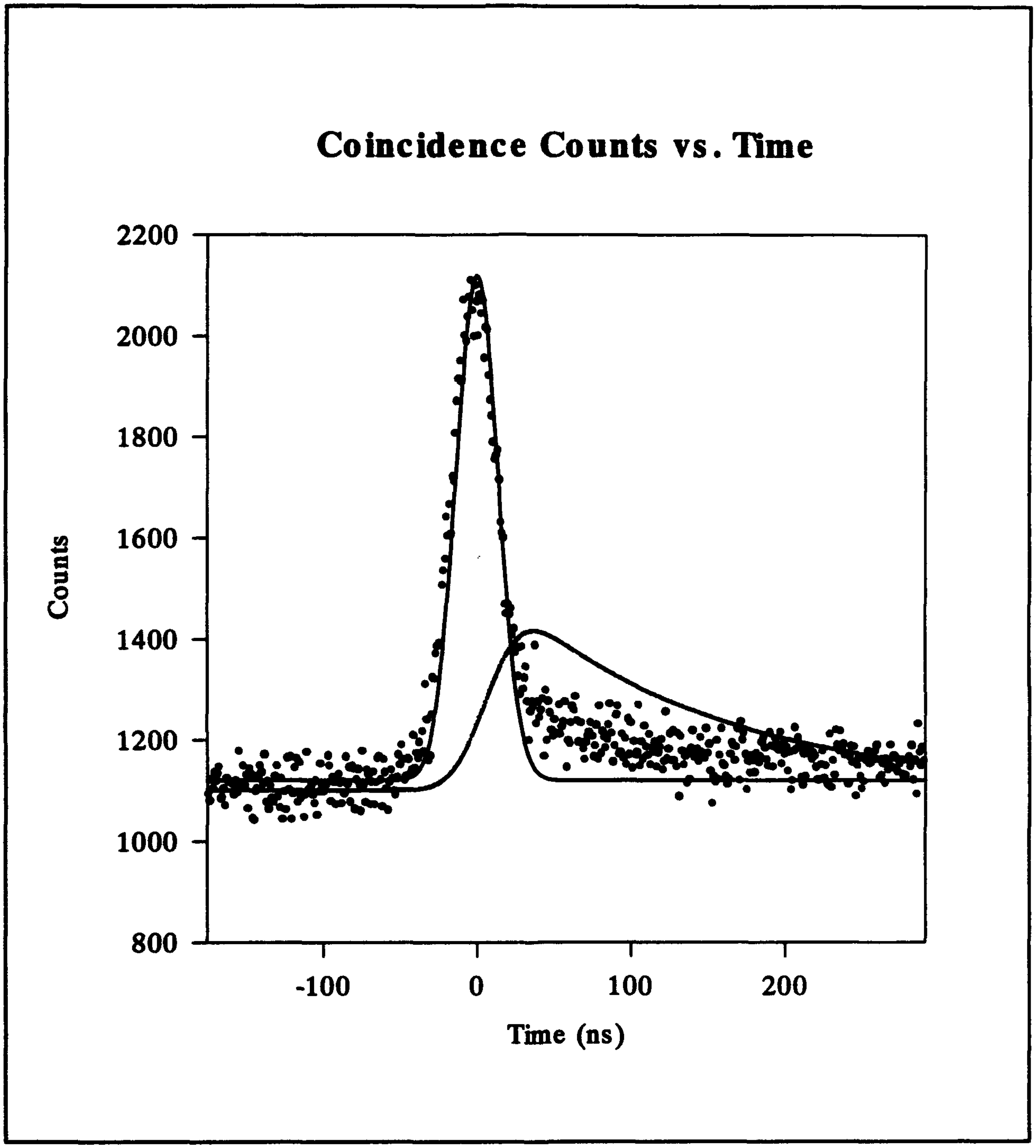

Figure 5. The "lifetime"curve for the 14.4 keV level obtained when the radiation traverses the sample. The solid-line curve shows the "prompt" component. The lower intensity dashed curve corresponds to a simulated component showing the normal lifetime curve. The data does not seem to have the normal lifetime behavior.

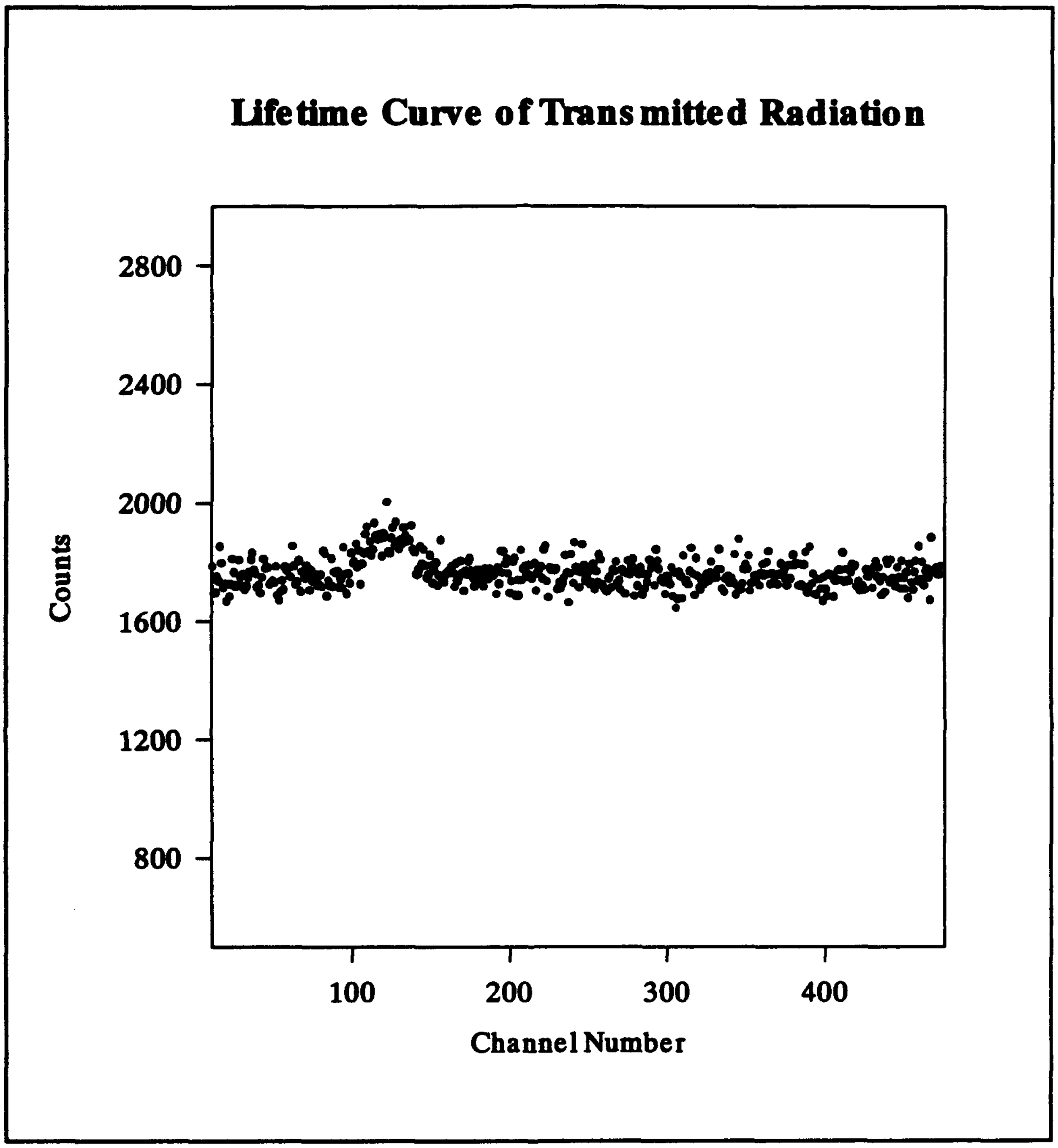

Figure 6. Our most recent result for the "lifetime" curve using one Ge detector and one NaI detector. The sample has been placed in a lead "washer" to eliminate detector "cross talk." (One hundred channels is about one hundred nanoseconds.